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Horizontal Cooperation in Network Expansion: An Empirical Evaluation of Gas Transportation Networks

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This research presents a coordination approach for the expansion of gas transportation networks to serve an increasing customer base. An empirical study of natural gas markets in the southeastern United States shows that horizontal cooperation among transportation service providers (i.e., pipeline companies) allows for expanding the gas transportation networks efficiently to serve new customers. The benefits of coordination are identified through key structural elements such as number and location of additional pipeline links, lower infrastructure expansion costs, and demand segmentation for the gas transportation service providers.

INTRODUCTION

The significant increase in demand for natural gas in the U.S. industrial sector has renewed a strategic interest in gas transportation networks. The scope of gas supply chains and scale of logistics activities are expanding to ensure an efficient supply of gas to an increasing number of customers. There are a number of factors that contribute to the increase in demand, such as moderate prices of natural gas relative to coal, discovery of abundant sources of domestic (shale) natural gas, and higher operational efficiency of gas-based technologies. The increase in demand has encouraged major investments in developing gas production capacity in the United States. In 2011, 95% of the total natural gas consumed in the country was produced domestically (Barteau and Kota 2014).

One of the largest consumers of natural gas in the United States is the electric power industry. Not only because a majority of the new electric power generation units being installed in the United States are based on gas-fired technology, but many old coal-fired power plants are being converted to use natural gas (Lapides et al. 2011). The addition of new and retrofitted power plants has increased the demand for natural gas, which exceeded 9.1 trillion ft3 in 2012 (EIA 2013). The projected increase in the demand for natural gas has raised concerns about logistics and transportation capabilities of the existing gas distribution networks. Unlike other surface (road and rail) transportation modes, capacity in a distribution pipeline is already in use by existing customers. In this case, expanding transportation networks to connect additional customers to gas supply requires careful consideration and planning.

This study contributes to the academic literature by proposing an arrangement for network expansion based on the concept of horizontal cooperation among competitors. In this setting, gas pipeline companies, which otherwise compete with each other, cooperate to serve respective segments of the market through mutual agreement. In a situation where a sizeable new demand for natural gas would result in an aggressive competition among pipeline companies, a strategy based on cooperation may provide a better alternative that is beneficial for partnering firms as well as customers. The benefits of coordinated expansion of gas transportation networks are analyzed and discussed in relation to extant theory. To develop this understanding, the logic of industrial organization theory and concept of horizontal cooperation among competitors is used.

The paper shows that horizontal cooperation can yield lower expansion costs while providing equal business opportunity for participating firms. The dynamics of gas transportation are represented by a network model, which also incorporates the requirements for expanding transportation infrastructure. This model includes relevant supply-demand requirements, network expansion costs, gas transmission capacity, and elements of gas pipeline infrastructure. Real-world data from gas pipelines in the southeastern United States are used in an empirical evaluation of the existing gas transportation networks to identify key strategic issues concerning collaborative network expansion. The scenario where different pipeline companies compete for gas supply business in a new market is compared with another scenario driven by the horizontal cooperation approach. The results provide empirical evidence that cooperation not only results in an efficient expansion of the pipeline network to support the needs of new customers (power plants) but also provides equal opportunities for partners firms (gas transportation service providers) in the new market.

BACKGROUND

In the past, a major concern about adequate sources of gas supply existed due to the limited domestic natural gas reserves. As late as 2007, the United States was expected to be increasingly dependent on imports due to the constrained domestic supply. As new technologies of horizontal drilling and hydraulic fracturing have increased domestic gas production, reliance on gas imports is no longer a major issue (Mouawad 2009; Yergin and Ineson 2009). According to the 2012 Annual Energy Outlook Report of the U.S. Department of Energy (EIA 2012), domestic shale gas supply is expected to increase from 10% of total gas production in 2010 to 49% by 2035, thus making domestic production of natural gas greater than the expected national demand. The domestic production capacity is estimated to satisfy demand for gas from large industrial users in the electric power generation industry (Paltsev et al. 2011).

The other key issue, which is relevant in this context, is the impact of federal environmental regulations. The electric power plants built in the U.S. had primarily used coal as a fuel in the combustion process to produce high pressure steam. Burning coal in this process releases greenhouse gases, which are harmful to the environment. To control the emission of greenhouse gases, the U.S. Congress passed new amendments to the 1963 Clean Air Act, which became effective January 1, 2012. These regulations limit the hazardous air pollutants emitted by coal-fired electric power plants (EIA 2012). The electric power companies are required to bring these coal-fired power plants into regulatory compliance or face significant monetary penalties. One of the options available to power companies is installing scrubbers, which capture sulphur oxides from coal combustion and filter them into disposable matter. However, this additional step in power generation adds a significant capital and operating expense for power companies, affecting the cost per unit ($/kilowatt-hour) of generated electricity. The lower efficiency and higher maintenance costs of old coal-fired power plants do not offer an economical case for recovering capital investments in the environmental retrofits (Shahidehpour et al. 2005). For these operational and financial reasons, power companies opted to replace coal-fired power plants with gas-fired technology, instead of installing environmental controls on the old coal-fired power plants (Lapides et al. 2011). The new power plants are typically built on the same sites as old coal-fired plants. The current sites are already connected to the national electric grid; they already have necessary approvals and permits for locating a power plant and the necessary human and infrastructure resources are in place.

The legislation enacted by the U.S. Congress, such as the Natural Gas Policy Act (1978) and Natural Gas Wellhead Decontrol Act (1989), deregulated the natural gas industry. Issued in 1992, U.S. Federal Energy Regulatory Commission (FERC) Order No. 636 states that "pipelines must separate their transportation and sales services, so that all pipeline customers have a choice in selecting their gas sales, transportation, and storage services from any natural gas provider, in any quantity." These legislative actions resulted in a competitive marketplace in which different players engage in the sales and purchase of transportation, storage, and distribution of natural gas.

The transportation of natural gas from a gas wellhead to the customer involves multiple organizations. The natural gas supply chain starts at its upstream end with gas production. The uniqueness of the natural gas supply chain is that it consists of a single product. All production sources are required to process the gas extracted from underground sources to meet the quality standards of natural gas. The output of natural gas wells is collected through a network of gathering pipes which deliver natural gas (with its impurities) to processing plants. These gas processing plants bring natural gas to the required national quality standards.

The other key player in the gas supply chain is gas storage companies. These companies operate underground storage facilities (such as aquifers, caverns, and old gas wells) where natural gas can be stored. The gas is injected under pressure into these storage areas and later extracted, as needed. Storage facilities help absorb demand fluctuations during the year. A significant aspect of the storage facilities is these are natural underground areas that are very expensive to duplicate above the ground. Thus, from a supply chain design perspective, storage locations and capacity are usually fixed.

The gas supplied by producers is purchased by gas distributors and marketing companies. The distributors are typically gas utilities which service customers in large cities and municipalities. Natural gas is delivered to city gates by pipeline companies from where a distribution company takes over and transports the gas to residential and commercial customers. Large industrial customers such as electric power plants typically buy gas directly from the gas pipeline companies and gas marketers due to higher end-of-line pressure requirements. The available supply of natural gas is also bought and sold through the marketing companies. Marketers provide coordination services such as purchase, storage, transportation, and all intermediate steps required to facilitate the sale and delivery of natural gas. A key service offered by marketing companies is managing the transportation arrangements between different pipelines. When natural gas in one pipeline is to be delivered to a customer located on another pipeline, gas transportation hub operators are instructed by the marketing companies to make pressure adjustments to transfer gas through these pipelines.

To study the effects of an increase in gas demand from new power plants, a strategic review of the natural gas transportation networks is required at the national level. Such a review would make recommendations for installing new capacity on existing lines and/or building new interstate pipelines. However, an evaluation at such a level involves many players and stake holders, increasing the scope of work, which is beyond the focus of this study. This paper is focused on a regional context and transportation/supply considerations for distribution pipeline firms. The empirical evaluation presented in this paper is focused on issues related to connecting new users (power plants) of natural gas to existing pipelines (under current capacity restrictions) and identifies the benefits of coordination in expanding gas transportation networks.

HORIZONTAL COOPERATION IN GAS TRANSPORTATION NETWORKS

The gas transportation network in the U.S. comprises more than 210 natural gas pipeline systems (EIA 2013). The 30 largest interstate pipelines transport about 80% of the total gas supply (EIA 2013). In the gas transportation industry, new capacity is added only when there are new customers in the market, such as the electric power industry where many power plants are undergoing a change in fuel from coal to natural gas. These developments in the electric power industry have presented a significant business opportunity for pipeline companies to expand their revenue base.

Industrial organization theory in the field of strategic management describes the dependency that exists among competitor firms that leads to the formation of strategic groups (Harrigan 1985). The concept of strategic groups serves as a foundation for the idea proposed by Sollner and Rese (2001) in which firms that would otherwise compete with each other mutually agree to each serve a different segment of the market. In this context, firms may elect to serve narrowly defined customers (based on some criterion, such as cost-to-serve) and thereby not compete head-on with their competitors in the same market. A strategic group may include many firms or just one member (single pipeline company), with each firm following its individual strategy (Audy et al. 2012; Sollner and Rese

2001). Formation of such groups protects its members from invasion by other competitors due to their relative cost position, among other factors (Caves and Porter 1977).

The concept of strategic groups can also be examined through a network of relationships among competitors (Zaheer et al. 2000). Bengtsson and Kock (1999) classified the nature of relationships among competitors into four different types, based on the continuum between cooperation and competition: coexistence (social and information exchange among partners, no economic exchange), cooperation (business, information, and social exchange), co-opetition (partners cooperate in some ways and compete in others) and competition (a zero sum arrangement). According to this classification, competitors can coexist in a market by keeping their distance and avoiding interaction. When competing firms do interact, they try to reduce conflicts through cooperation. This situation arises when competitors have common goals (e.g., when pipeline companies decide to cooperate in facilitating gas connectivity to power plants to promote use of natural gas in electric power generation). The cooperation among competitors does not necessarily mean they do not compete with each other. Under co-opetition, competitors can cooperate in one market, such as power generation market, and compete in others, such as industrial and residential markets (Bengtsson and Kock 2000). In this paper, our focus is on cooperation among firms (pipeline companies), which operate at the same level in the gas supply chain, referred to as horizontal cooperation (Cruijssen et al. 2007b). Through close cooperation and joint planning, partner pipeline companies can increase the competitiveness of their gas transportation networks (Vanovermeire et al. 2013).

The existing literature in the area of horizontal cooperation in logistics has focused on issues related to pooling of transportation resources, leveraging specific strengths and capabilities of the other participating firms, trading of complementary resources to achieve mutual gains, and to eliminate the high cost of duplication (Schmoltzi and Wallenburg 2011; Vanovermeire et al. 2013). Empirical research has indicated that horizontal cooperation can result in decreased cost, improved service, and protection of market position (Cruijssen et al. 2007c). According to Vos et al. (2002) synergies from cooperation among competitors can be achieved by restructuring transportation networks collectively by all partners. This approach was shown to yield benefits for all participant firms in the German consumer goods industry (Bahrami 2002). Cruijssen et al. (2007a) provided empirical evidence that horizontal cooperation provides cost savings for logistics service providers through joint planning of transportation routes.

Horizontal cooperation uses market segmentation based on two characteristics: how well market needs align with the capabilities of individual partner firms, and that each market segment offers an equal business opportunity to partner firms (Krajewska et al. 2007; Audy et al. 2010; Vanovermeire et al. 2013). The gains resulting from horizontal cooperation are measured in the form of cost savings (through increased efficiency, economies-of scale, and joint purchase power) and revenue opportunities. In the context of this research, pipeline companies may jointly coordinate market segmentation to identify a group of customers to be served by each partner firm, based on network expansion costs. Such a cooperative arrangement should provide equal opportunity to all participants for generating revenue. The feasibility of such an arrangement is supported by the limited transportation capacity of gas pipelines, which does not allow pipeline firms to compete in all markets and serve all customers.

In the next section, a model is presented that represents the gas transportation networks through various structural elements such as footprint of existing pipelines, routing options for expanding the network, demand and supply requirements, and optimal routes for installing new pipes.

NETWORK MODEL OF GAS TRANSPORTATION

A gas transportation network can be represented by a model using a graph composed of a collection of nodes and links. The footprint of a pipeline is identified by links which pass through different nodes. The nodes represent geographical locations and facilities (demand points and branching stations).

Additional requirements, such as transportation capacity, demand and supply requirements, and routing restrictions, can be added to the network model. The output of the model identifies optimal routing for installing new pipes and pressure stations, so that new demand nodes can be connected to supply nodes through the existing pipelines.

Earlier research has shown that optimal network configuration of gas pipelines has a tree-like structure (Rothfarb et al. 1970; Bhaskaran and Salzborn 1979). Thus, the minimum spanning tree approach provides a good basis for a mathematical model of gas transportation networks (Kawatra and Bricker 2000). The network model used in this paper follows this approach with updates to implement the network expansion requirements specific to the case studied here. The model is used to study different strategic issues related to pipeline expansion, i.e., which existing gas pipeline is most suitable to supply natural gas to the electric power plants, routing of pipes for the new pipelines, consideration for available gas capacity, and the location/size of new gas pressure regulation stations.

Unlike freight transportation and telecommunication networks, a design of gas pipeline networks has to consider additional issues such as gas pressures, flow rates, and pressure regulation (Martin et al. 2006). The literature on pipeline networks is generally focused on optimizing the routing of pipeline networks, selecting diameter of the pipes (related to transmission capacity), and location of pressure regulation stations (Zheng et al. 2010; Kabirian and Hemmati 2007). For expanding an existing gas pipeline network, a major area of interest is in selecting the segments of pipeline where reinforcements are added to satisfy increasing demand (Babonneau et al. 2012; Andre et al. 2009).

Due to long distances between the gas-wells and demand points, pressure regulation stations are widely used in transporting natural gas. The gas regulation stations provide pressure differential across a pipe to control the flow of gas. The pressure regulation is modeled in the form of inlet and outlet pressures on each arc in a network graph (Rios-Mercado et al. 2002). The inlet and outlet pressures across an arc determine the direction of gas flow.

Modeling Framework

The network model used in this paper is based on a grid-based graph that represents a geographical region, in terms of nodes and links. The grid is useful in identifying population centers, environmentally protected land, and other right-of-way areas through which pipelines cannot pass. Such no-go areas are identified by disconnecting the corresponding nodes from the other nodes in the graph. The nodes in the graph are represented by N, which consists of nodes through which existing pipelines pass (represented by set P), nodes to represent the locations of power plants (set K), and nodes through which new pipes can be routed (set R). The node set P is further partitioned into subsets, represented by P_g, where each subset of nodes corresponds to different pipelines (indexed by g). The connectivity within P_g is implemented by setting c_{ij}=0, for nodes i and j that are inter-connected. Otherwise, c_{ij} represents the unit cost of installing a new link between nodes i and j. Each pipeline node (indexed by l) in subset Pg is characterized by its gas pressure (pounds per square inch), denoted by π_l. The gas flow supply (ft^3/day) available in a pipeline g is represented by κ_g. This parameter can be used to include additional gas supply in the future, as more shale gas fields are added to the supply network. The supply of natural gas to a power plant is needed at a specific pressure π_k under the condition $\pi_k < \pi_l$. In order to meet these gas pressure requirements, pressure regulation may be needed. A pressure regulation station can be installed at a unit cost of γ per psi of gas pressure.

The supply of natural gas to a power plant requires laying new pipes. The model finds the lowest cost path by routing new pipes through available nodes to one of the existing gas pipelines. The demand-supply matrix D provides the details about the sources (gas pipelines) and demand (power plants) of gas supply. An element dik of matrixD of the supply-demand matrix represents a demand node (power plant) by -1, supply node (gas pipeline) by +1, and connector node by 0. Note that for each power plant, there may be multiple sources of supply (pipelines). Hence each column of the demand-supply matrix will have a single -1 entry and multiple +1 entries.

There are three types of decision variables in the model. The decision variables X_{ij}^{k} represent the binary choice of using link (*i,j*) for routing the new pipeline to supply natural gas to power plant *k*. Note that for two different power plants k and m, X_{ij}^{k} and X_{ij}^{m} variables may use the same link (i,j), especially if *k* and *m* are to be connected on the same branch of the new pipeline. To properly identify all the links on which new pipes will be installed, binary decision variables Y_{ij} are used. These variables properly identify the links on which new pipelines will be constructed, based on the X_{ij}^{k} variables. The decision variables P_l represent the difference in gas pressure between what is currently available at a gas pipeline node *l* and the pressure that is needed at the end-of-line power plant(s). If there is a pressure differential, additional pressure regulation capacity may need to be installed on the pipeline.

Sets:

G = Existing gas pipelines; $\{1, 2 \dots g\}$

P_g = Nodes associated with gas pipeline *g*

K = Nodes where new gas-fired electric power plants k are located

R = Available nodes for new pipelines,

N = Set of nodes

E = Set of links

Parameters:

c_{ij} = Cost of installing new gas pipeline on link (*i,j*)

γ = Cost to add unit pressure regulation (psi) at a gas pipeline node

d_{ik} = Natural gas supply-demand matrix

κ_g = Flow capacity of pipeline *g*

α_k = Gas requirement at power plant

π_l = Available gas pressure at pipeline node *l*

π_k = Gas pressure requirements at power plant *k*

M = Large number

Decision Variables:

X_{ij}^{k} = 1, if link (*i,j*) is needed to supply gas to plant *k*; 0 otherwise

Y_{ij} = 1, if gas pipeline is constructed over link (*i,j*); 0 otherwise

P_l = Pressure differential (psi) required at pipeline node *l*

Model Formulation:

$$(1)\quad (\boldsymbol{P})\quad \min_{(i,j)\in E} c_{ij}Y_{ij} + \sum_{l\in P} \gamma\, P_l$$

Subject to:

$$(2)\quad \sum_{(i,j)\in E} X_{ij}^{k} - \sum_{(i,j)\in E} X_{ji}^{k} \leq d_{ik} \qquad ;\forall\, k \in K, i \in N$$

$$(3)\quad \sum_{k\in K} X_{ij}^{k} \leq M\, Y_{ij} \qquad ;\forall\, (i,j) \in E$$

$$(4)\quad \sum_{k\in K, i\in P_g, j\in P_{q\neq g}} X_{ij}^{k} = 0 \qquad ;\forall\, g \in G$$

(5) $$\sum_{k \in K, i \in P_g, j \in R \cup K} \alpha_k \; X_{ij}^k \quad \leq \quad \kappa_g \qquad ; \forall \, g \in G$$

(6) $$\sum_{j \in R \cup K} (\pi_l - \pi_k) \; X_{ij}^k \quad \leq \quad P_l \qquad ; \forall \, l \in P, k \in K, \pi_l \geq \pi_k$$

$$X_{ij}^k, Y_{ij} \;\; \in \{0,1\}; \; P_l \geq 0 \qquad ; \forall \, (i,j) \in E, k \in K, l \in P$$

The objective function (1) represents the total expansion cost of the transportation network. The first term of the objective function deals with the total cost of installing new gas pipelines. The total cost of adding new or updating existing pressure regulation stations at pipeline node l is given by the second term, using decision variables P_l. The objective function is minimized over a number of constraints. Constraint (2) is used to find the lowest cost path from each power plant to one of the available pipelines for gas supply. For a given index i in constraint 2, index j in the two summations, is from two different instances of set E. Hence, node j marks the end of one link as well as the start of another link. These constraints consider multiple root-nodes where demand for plant k can be serviced. These root-nodes correspond to different supply pipelines. The links (pipes) are installed to service a power plant based on the smallest branch length to a root-node. If needed, multiple power plants can be connected together through tree-like paths. Constraint (3) is used to identify the links where new pipeline(s) will be constructed. A new pipeline cannot be installed to bridge (connect) two or more existing pipelines, as represented by constraint (4). Constraint (5) ensures that demand of natural gas from the newly constructed/retrofitted power plants to an existing pipeline does not exceed its available supply. In order to meet the gas pressure requirements of the power plants connected to the new pipelines, pressure in the supply pipelines may have to be adjusted. Constraint (6) determines the difference between available gas pressure (at different supply pipeline nodes) and gas pressure requirements at all the power plants connected to supply pipeline node l. The requirements of pressure regulation are determined by the largest pressure differential among all supply and demand points on a branch. Note that there may be some adjustments of gas pressure needed at delivery points for specific customers. However, in a model focused on network-level considerations, local operational details are not included.

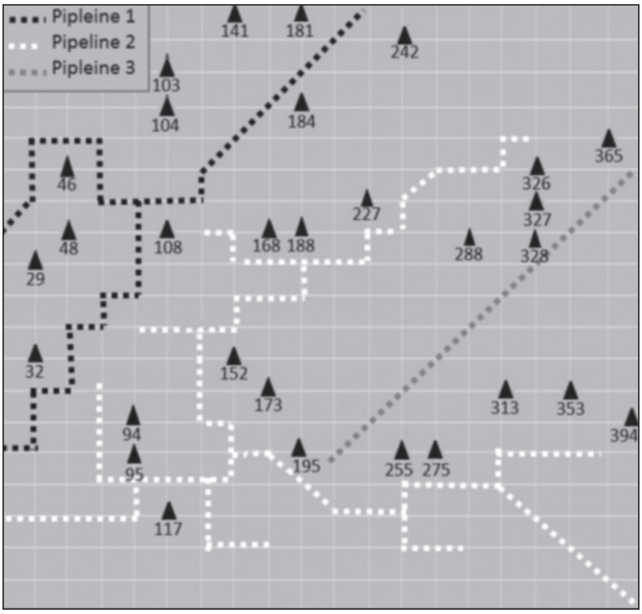
The output of the model provides optimal routing of new pipes, which connect the demand points (power plants) to the most suitable supply point (gas pipeline) such that expansion costs of the new pipes and pressure stations are reduced while considering demand requirements and supply restrictions. This model is used to evaluate the differences between the uncoordinated and coordinated approaches for expanding the gas transportation networks. The differences are measured in terms of the expansion costs, which are based on routings of new pipes, supply and demand points in the network, and installation of pipes and pressure stations. The benefits of horizontal cooperation in network expansion are explored through a study of gas pipelines and power plants in the southeastern U.S. region.

SOUTHEASTERN U.S. GAS PIPELINE ENTWORK

This section presents a study to analyze key issues related to pipeline expansion in order to serve the demand from the new gas-fired power plants in the southeastern United States. The study considers three major interstate pipelines in the region; Southern Natural Gas, Transco, and Kinder Morgan. Kinder Morgan pipeline originates from three locations in southern Louisiana and southern Texas, converging around Nashville, TN. From there the pipelines travel through Kentucky and then on through Ohio to Boston and New York. Southern Natural consists of two main lines through the southeast region, one of which originates in southern Louisiana and the other originating in northern Louisiana. Both lines pass through Mississippi and Alabama, and terminate in Georgia. Transco is the third major pipeline that runs through the southeast region. It originates in southern Texas and terminates in the State of New York, passing through Georgia, South Carolina, and North Carolina, before reaching New York. These pipelines are identified in Figure 1 as Pipeline 1 (Kinder Morgan), Pipeline 2 (Southern Natural), and Pipeline 3 (Transco).

The geographical area of this study is represented by a graph (Figure 1), which comprises 400 nodes on a 20x20 grid where vertical (horizontal) distance between two nodes represents 50 miles (diagonal distance is 70 miles), covering a total area of one million square miles. The study includes 30 nodes, which represent new gas-fired power plants, and 103 nodes, which represent the existing gas pipelines. The power plant and pipeline nodes are inter-connected through a set of 1,484 horizontal, vertical, and diagonal arcs. These arcs are used to route new pipes from existing gas pipelines to new gas-fired power plants.

Figure 1: Gas Pipelines and Power Plants



The coal-fired power plants included in this study operate in Alabama, Georgia, Tennessee, Kentucky, South Carolina, and North Carolina, each with a power generation capacity larger than 600MW. There are 30 such plants in these six states with an average size of 1,581 MW. The smallest is 601 MW and the largest plant is 3,564 MW. The data on each power plant (location, year built, power generation capacity, current financial liabilities, and carbon costs) were extracted from the U.S. Energy Information Administration (EIA) and industry databases related to the energy industry (Table 1). In Figure 1, power plants are identified by their ID in Table 1.

The cost of installing a new gas pipeline link is set at $1 million per mile (INGA 2009). The demand for natural gas at the electric power plant is calculated using the estimates provided by EIA, i.e., 0.00789 MCF of gas is used per KWh of generated electrical energy (EIA 2013). The supply nodes (gas pipelines) can provide gas pressures that range between 900 psi and 1100 psi, while the pressure requirements at the power plants range between 400 psi and 600 psi (Kabirian and Hemmati 2007). The data about gas supply capacity in the three pipelines were obtained from the respective gas companies: P1 – 106 MMCF/day, P2 – 25,000 MMCF/day, and P3 – 25,000 MMCF/day.

Table 1: Power Plants

Plant ID	Location (State)	Plant Name	Generation Capacity (MW)	Natural Gas Demand (MMCF)	Natural Gas Pressure (psi)
32	AL	Colbert	1250	342	579
94	AL	Gorgas	1417	387	558
95	AL	Miller	2822	771	644
117	AL	Gaston	2013	550	652
152	GA	Hammond	953	260	520
173	GA	Bowen	3499	956	662
195	GA	Yates	1487	406	553
255	GA	Scherer	3564	974	523
275	GA	Harllee Branch	1746	477	647
46	KY	Paradise	2558	699	571
103	KY	Cane Run	654	179	571
104	KY	Mill Creek	1717	469	604
141	KY	Ghent	2226	608	592
181	KY	H L Spurlock	1279	350	503
184	KY	E.W.Brown	739	202	623
242	KY	Big Sandy	1233	337	669
288	NC	Cliffside	780	213	477
326	NC	Marshall	1996	546	630
327	NC	Riverbend	601	164	566
328	NC	GG Allen	1155	316	621
365	NC	Belews Creek	2160	590	625
313	SC	Urquhart	650	178	469
353	SC	Wateree	685	187	505
394	SC	Williams	633	173	588
29	TN	Johnsonville	1485	406	580
48	TN	Cumberland	2600	711	502
108	TN	Gallatin	1255	343	652
168	TN	Kingston	1700	465	669
188	TN	Bull Run	950	260	472
227	TN	John Sevier	800	219	494

RESULTS AND ANALYSIS

To study the effect of coordination in expanding gas transportation networks, model (P) was used with data in two main scenarios. In the first scenario, a coordinated expansion of gas transportation networks was undertaken to identify a pipeline (among all candidate pipelines) which will serve a specific power plant. Since expansion of a pipeline network represents a significant portion of the cost of developing the capability to serve customers, it follows that a successful firm would be the one that can serve customers with lowest network expansion costs. We use this setting to select which pipeline will service a specific power plant based on the lowest total transportation network expansion costs. The second scenario is based on connecting power plants to the network of each pipeline company, separately. This setting corresponds to the uncoordinated expansion of the gas transportation network. Note: A pipeline firm may choose to serve all or a part of the market. Our intent in using the two alternative scenarios is for the purpose of comparison.

The model and corresponding data was coded into AMPL, which integrates a modeling language for describing optimization data, variables, objectives, and constraints (Fourer, Gay and Kernighan 2002). The model was solved to optimality using CPLEX 12.4 solver for linear mathematical programming models. The outputs of the model from both scenarios were compiled to provide information about: (i) which pipeline is most suitable for supplying natural gas to power plants based on the pipe installation costs and available gas supply, (ii) number and location of new branches added to the existing pipelines, (iii) new pipe links installed, and (iv) power plants allocated to each supply pipeline for service. The outputs of these scenarios were compared using key structural elements such as number and location of new links, expansion costs, and the allocation of power plants to gas pipelines for service. The best option is characterized as one that adds the least number of new branches with fewest pipes added to the network, and one that will need the smallest pressure differential between supply pipelines and power plants. These choices lead to a least cost expansion of the gas transportation network.

The solution of the model in AMPL identifies the links that are used for installing gas pipes to service each power plant. These links were identified by the start and end nodes (indexed by i and j in the model). This information was recorded for each pipeline and power plant in the case study. For each pipeline, the number and location of pressure regulation stations were also recorded. The scale used in the grid to represent the network graph was used to calculate the length of new pipe links. These detailed outputs were compiled into summary tables, which are discussed below.

The summary output of the first scenario is presented in Tables 2 and 3. The results show that in a coordinated expansion of the gas transportation network, each pipeline serviced a similar proportion of natural gas demand in the case study, e.g., pipelines P1 and P3 serviced 31% and 26% of the total gas demand, respectively (see last column in Table 2). Thirty-three percent of the power plants were connected through pipeline P1, 40% were connected through P2, and 27% were connected through pipeline P3. The significance of this result is related to the concern that by participating in collaborative planning, pipeline companies lose the opportunity to capture market share and that some participants will be at a disadvantage in this arrangement. As the results show that for the southeastern region, the footprint of pipeline networks and the geographical dispersion of customers (power plants) allow participant pipeline companies to share a similar proportion of business opportunities in the new market.

Table 2: Pipeline - Power Plant Allocations

Plant Name (ID)	Location	Plant Name (ID)	Location	Plant Name (ID)	Location
Colbert (32)	AL	Gorgas	AL	Yates	GA
Paradise (46)	KY	Miller	AL	Harllee Branch	GA
Cane Run (103)	KY	Gaston	AL	Cliffside	NC
Mill Creek (104)	KY	Hammond	GA	GG Allen	NC
Ghent (141)	KY	Bowen	GA	Belews Creek	NC
H L Spurlock (181)	KY	Scherer	GA	Urquhart	SC
E.W.Brown (184)	KY	Marshall	NC	Wateree	SC
Big Sandy (242)	KY	Riverbend	NC	Williams	SC
Johnsonville (29)	TN	Gallatin	TN		
Cumberland (48)	TN	Kingston	TN		
		Bull Run	TN		
		John Sevier	TN		

Additional outputs of this scenario are shown in Table 3. The analysis shows that network expansion (and related costs) for each pipeline depends on its existing footprint. While pipelines P1 and P3 served new customers with about the same total natural gas demand (i.e., 31% and 26%, respectively), each pipeline's costs for installing new pipes was different. Pipeline P1 added 16 new links with a total length of 920 miles. Whereas, for a similar number of customers and gas demand, pipeline P3 needed 28 new links (75% more links that P1) for a total length of 1,520 miles. For pipeline P1, this level of expansion accounts for a significant increase (about double the length) compared with 630 miles of existing pipeline in the area (Kinder Morgan 2014).

Table 3: Summary Statistics of Expanded Pipeline Network

Pipelines	Plants Served	New Pressure Stations	New Links	Length of New Pipes	Gas Demand Serviced (MMCF)
P1	33%	8	16	920 mi	31%
P2	40%	8	18	980 mi	43%
P3	27%	2	28	1520 mi	26%

These results identify a potential shortfall for pipeline companies which view the network expansion decision myopically. The potential to capture a large share of the market is tempting until the reality of cost-to-serve is considered in the analysis. These results show that for some pipeline companies, the cost of expanding their current pipeline network may come at a prohibitively high cost. Conversely, a pipeline may have a footprint in a region that allows it to efficiently expand its services to new customers. Such is the case with the pipeline network of Southern Natural (Pipeline P2), which has an existing network footprint in the region that is well-suited for providing access to the power plants within the region. The pipeline P2 is allocated 40% of all the new customers in the study (most among all the pipelines), which account for 43% of all the demand from the new gas-fired power plants. These power plants are connected through 18 new pipe links (29% of all new links installed) with eight pressure regulation stations (same as pipeline P1). The total length of new pipes added to pipeline P2 (980 miles, see Table 3) accounts for a 29.8% increase to the existing

3,300 miles length of pipeline P2 in the region. This is the smallest percentage increase for a pipeline in the case study, and yet it covers the largest proportion (43%) of new demand.

Next, network model (P) is used in the uncoordinated case. Recall that in this setting, each pipeline company is considered individually to satisfy the demand from all power plants. The network model in this scenario identifies the optimal expansion of each pipeline's network, exclusively. The output of the model identifies the layout and routing of the new pipes in the expanded network of each pipeline. The output of the model for each pipeline is shown in Table 4. Note that for comparison, output of the previous scenario (coordinated expansion) is listed as base case.

Table 4: Comparison of Pipeline Networks

	Base Case	**Case: P1**	**Case: P2**	**Case: P3**
Network Expansion Costs ($M)				
Pipe Installation	2,060	3,960	3,710	4,910
Pressure Regulation	549	363	419	237
Total	2,609	4,323	4,129	5,147
Number of new branches	15	8	13	4
Plants serviced per branch (Avg.)	1.75	4.14	2.15	7.5
Number of new links	41	66	59	81
Length of new pipes (miles)	3,420	3,960	3,310	4,610

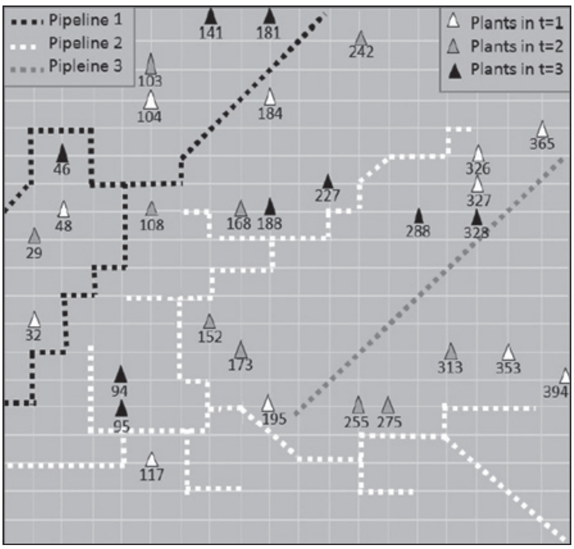
In the case of pipeline P1, all customers were connected by adding 66 new links (61% more links than base case). The new branches added to the original pipelines connect through eight locations, where half of these locations were different from the base case. The number of power plants serviced on each branch averaged 4.14, which is almost 2.5 times higher than the base case. This shows that pipeline P1's network requires a lot more dense expansion than the base case. The costs of installing new pipes on pipeline P1 were very high (92.2% compared with base case). In the case of pipeline P2, only two of the branch locations were common with the base case. Compared with pipeline P1, P2 used a higher number of branches (62% more) and a smaller number of power plants serviced by each branch. While the average number of plants on a branch (Avg. = 2.15) was still higher than the base case, pipeline P2 needed (44%) more pipe links to provide access to its customers. This caused the expansion costs of pipeline P2 to be much higher than the base case.

These results show that in expanding a pipeline network with an extensive footprint (such as pipeline P2), power plants were connected separately on a branch from the supply pipeline. When the pipeline network is not as extensive (as in the case of Pipeline P1), multiple power plants were connected together for service within a single branch. This observation was verified in the case of pipeline P3 (see Table 4). The data provided by the pipeline companies for this case study show that pipeline P3 has the sparsest network in the southeastern region. The result of the scenario identified that 81 new pipe links will be needed to connect all customers (power plants), which would add 4,610 miles to the existing network. The total expansion cost in the case of pipeline P3 was the highest among all the pipelines. However, there were only four new branches used by P3 to service power plants, with an average of 7.5 power plants served per branch. This is the highest number of power plants per branch among all the pipelines, increasing the utilization of the newly installed pipes.

The analysis presented above is based on the evaluation of gas pipeline networks to provide connectivity and service demand of all power plants. In this context, the results of the study has identified collaborative planning as the best approach toward expanding gas transportation networks. However, the power plants in question may have their own dynamics in terms of when a power plant may decide to switch fuel and its demand of natural gas becomes active. This situation introduces a time-based dimension to the pipeline expansion decisions. In this situation, the benefits of coordinated network expansion may be affected. For the purpose of this study, the timed-demand of natural gas for the coal-fired power plants in the region was evaluated based on the operational, financial, and environmental credentials of each power plant. This evaluation is made to identify the time when demand for natural gas at each power plant will be active. Note that this is an experimental evaluation, as the timing information about when demand of gas for a power plant will be active is not publicly available.

For this part of the study, three time periods were considered (each period was set equal to four years, which is similar to the time frame involved in replacing an existing power plant and building a gas pipeline). The timed-demand of each power plant is determined by considering the fixed (capital) and variable (operational) costs. The fixed costs included in the evaluation are replacement cost of a new gas-fired plant and a power plant's current financial liabilities. The replacement costs are assumed to increases in each future time period at the rate of 10% annually, and the financial liabilities decrease at the same rate in the future time periods. The variable costs considered in the evaluation are fuel costs (coal and natural gas) and carbon emission costs. The data and information related to this evaluation were obtained from power company websites, energy council reports, and government agencies such as EIA and Environmental Protection Agency (EPA). To identify the time when gas demand of each power plant may become active, total costs were computed for the following four options: (a) coal-fired plant is replaced in t=1, (b) replaced in t=2, (c) replaced in t=3, and (d) fuel in the plant is not replaced. For each of these options, fixed and variable costs were used to calculate the total costs of each option. Based on these calculations, a time period is identified when switching fuel will result in the lowest total cost over the entire planning horizon. The result of this evaluation is shown in Figure 2. Each power plant is color coded (white, grey, and black) to identify the time period when its time-demand is activated. Note that while this evaluation is experimental and actual timed-demand may have a different pattern, this setting allows us to investigate the effect of timed-demand on the benefits of using the coordinated network expansion approach.

Figure 2: Timing of Natural Gas Demand



The network model was used to obtain optimal (expanded) network structure in each planning period separately. In each case (time period), pipelines that provide the lowest cost connection to the demand-active power plants were selected. This selection was made while evaluating all candidate pipelines, similar to the approach used in the previously considered coordinated expansion scenario. The output from the timed-demand case is compared with the case of coordinated expansion (referred to as the base case) in Table 5. This comparison showed that demand timing adversely affected the total expansion costs. The results show that by spreading demand across different time periods, more branches were installed to provide access to power plants. This setting did not offer the same economies of scale as were realized in the case of pooled demand. A branch installed for servicing customers in a specific time period had no capacity left over for customers that may need supply beyond the time frame when a pipeline was extended. This limitation resulted in using more branches and installing additional pipes compared to the previously studied, coordinated expansion case of pooled demand. It is interesting to note that in the timed-demand case, market share of the pipeline companies did not change. Each company still held about the same power plant assignments, as shown previously in Table 2. These results show that network expansion costs will generally increase when power plants selectively switch fuel and activate their gas demand. To avoid this shortfall, it is worthwhile for the gas pipeline industry to engage major power companies in the decisions related to fuel-switch and the corresponding expansion of gas transportation networks. This collaboration will help all parties to develop a plan that can yield dividends in the form of lower expansion costs, which result from pooling demand.

Table 5: Effect of Timed Demand

	Timed Demand Case	Base Case
Network Expansion Costs ($M)}		
Pipe Installation	2,310	2,060
Pressure Regulation	821	549
Total:	3,132	2,609
Power Plants serviced by:		
Pipeline P1	10	10
Pipeline P2	11	12
Pipeline P3	9	8
Number of branches added:		
Pipeline P1	8	6
Pipeline P2	8	7
Pipeline P3	3	2

CONCLUSIONS

This paper highlights recent developments in the natural gas and related industries, which have renewed a strategic interest in gas transportation networks. The case of the electric power industry, one of the largest users of natural gas, is discussed. The prevalence of gas-fired technology in the electric power plants currently being built and switching of fuel to natural gas in coal-fired power plants have created a significant opportunity of revenue growth for pipeline companies. This paper presented a collaborative approach, based on the concepts of horizontal cooperation and strategic groups, which provides a system-level view of these opportunities for the competing pipeline companies.

The results of the study demonstrated that cooperation among pipeline companies provides mutual benefits for partnering firms and allows for better revenue opportunities through competitor-oriented market segmentation. The market segmentation was based on a cost-to-serve criterion. This approach allocates customer demand to a pipeline, which can provide access to natural gas with the least network expansion costs. The coordinated approach not only assured an equal opportunity for participant firms in the study, it also resulted in an efficient gas distribution network.

The paper also discussed the uniqueness of gas transportation networks compared to other modes of surface transportation. The supply-demand requirements, network expansion costs, transmission capacity, and elements of gas pipeline infrastructure were represented in a network model. The study presented in this paper identified key structural elements such as number and location of new links, expansion costs, and the allocation of power plants to gas pipelines for service. The results showed that for a pipeline company, cost-to-serve new customers depend on the footprint of its existing network. In one case, Transco Pipeline (P3) needed to install 75% more pipe links than Kinder Morgan pipeline (P1) to provide service to similar number of customers. Conversely, a pipeline may have a footprint in a region that allows it to efficiently expand its services to new customers, such as Southern Natural pipeline (P2).

The results identify an effect of economies of scale in network expansion under demand-pooling. With respect to this effect, multiple demand points are connected on the same branch, which results in installing fewer pipe links and pressure regulation stations. The results also show that expanding pipelines with a sparse footprint (such as pipeline P3 operated by Transco) results in fewer branches that service multiple customers, thus increasing the utility of the newly added pipeline branches. These results are useful for decision makers and network planners in the gas pipeline industry where network expansion planning is becoming ever more critical, given the increase in industrial demand of natural gas. The results from an experimental study showed that joint decision-making by coal-fired power plants and pipeline companies in determining the timing of activating gas use will be helpful in maximizing the benefits of collaborative expansion of gas transportation networks. Such an approach can maximize the benefits for all parties.

As with any research, there are some limitations of our study. In this study, the benefits of cooperation were evaluated based on economic considerations, i.e., cost-to-serve in terms of expansion of gas transportation networks. This study considered demand and connectivity issues with respect to coal-fired power plants. Additionally, the demand of natural gas for newly installed power plants can also be included. Although power plants are a big consumer group, there are other important consumers of natural gas as well, such as industrial plants, commercial businesses, and residential communities, which may also influence business consideration for pipeline companies and impact their network expansion decisions. Since market dynamics may vary by regions, an extension of this paper would include additional case studies to determine the benefits of the proposed approach across different market segments in the gas transportation industry. This paper evaluates the impact of horizontal cooperation from the point of view of infrastructure expansion costs. Adding considerations for strategic interactions and ways firms compete in the natural gas market would provide another avenue to extend this research.

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